2.4.1.7 Plum Creek, Colorado - June 13-20, 1965 (76). During the period of June 13-20, 1965, heavy rains fell over the eastern foothills of Colorado, very near the location of the Cherry Creek storm (47) (sec. 2.4.1.5). These rains reached total amounts of over 10 in. at many locations during the period, with the greatest point rainfall amount recorded being 18.1 in. The heaviest rains during the storm period occurred primarily in severe convective storms during the afternoons and evenings. Strong advection of unstable moist air from the Gulf of Mexico provided low level moisture for the storm.

On the 13th through the 16th (fig. 2.15-2.16), weak frontal systems were present in the Colorado region. The convective storms developed in the warm moist southerly air flow. The cold front to the west gradually ceased its eastward movement and became a stationary front by the morning of the 15th. The warm front gradually dissipated as a high pressure system moved rapidly southward from Canada. By the morning of the 16th, the center of the High was near the northern edge of the Great Lakes. The 500-mb chart (fig. 2.16) showed a trough over the west slowly intensifying as a closed Low center moved southward to a position over the California-Nevada border. Over the storm area the wind gradually backed, becoming easterly, and increasing in strength.

During the 17th, 18th, and 19th, (fig. 2.16-2.17) the surface High continued to move southward and by the morning of the 19th was centered over eastern Tennessee. The circulation around the High continued to bring warm moist air northward over the western Great Plains and eastern Colorado. The weak stationary front, located along the east-facing slopes of the Rocky Mountains, marked the westward extent of the moist air. At 500 mb, the closed Low over the California-Nevada border weakened, but an elongated trough remained over the western United States, while through the Great Plains a weak ridge extended from the Gulf of Mexico northward to the Canadian border. The air flow over the western and central United States was southerly from the surface to 500 mb. Moisture was flowing into the region through a deep layer of the atmosphere.

During the 19th, the north-south circulation began to break down. The surface High began moving eastward through Canada. This permitted the cold front extending southward from a Low over northern Canada to move into Colorado, causing the wind flow over western Colorado to shift to the northeast. At 500 mb, the trough and ridge both weakened and the flow over Colorado veered to westerly. These changes in the circulation ended the precipitation over Colorado.

The instability of the air mass over Colorado along the moisture inflow path at the surface is evidenced by the vertical variation in temperature and dew points shown in radiosonde observations taken at various stations during the storm. Representative soundings are shown in figure 2.18. These soundings show deep layers of conditionally unstable air that required only minimal lifting to release the instability. This initial lifting was readily available in Colorado as a result of diurnal heating and both terrain and frontal lifting.

Thunderstorms initially broke out over eastern Colorado on the afternoon of the 13th. Severe storms occurred every day with many reports of large hail and funnel clouds over the next 5 days. Squall lines can be detected on the afternoon and evening surface synoptic maps (not shown) on several days during this period. Although not always detectable with the synoptic scale weather

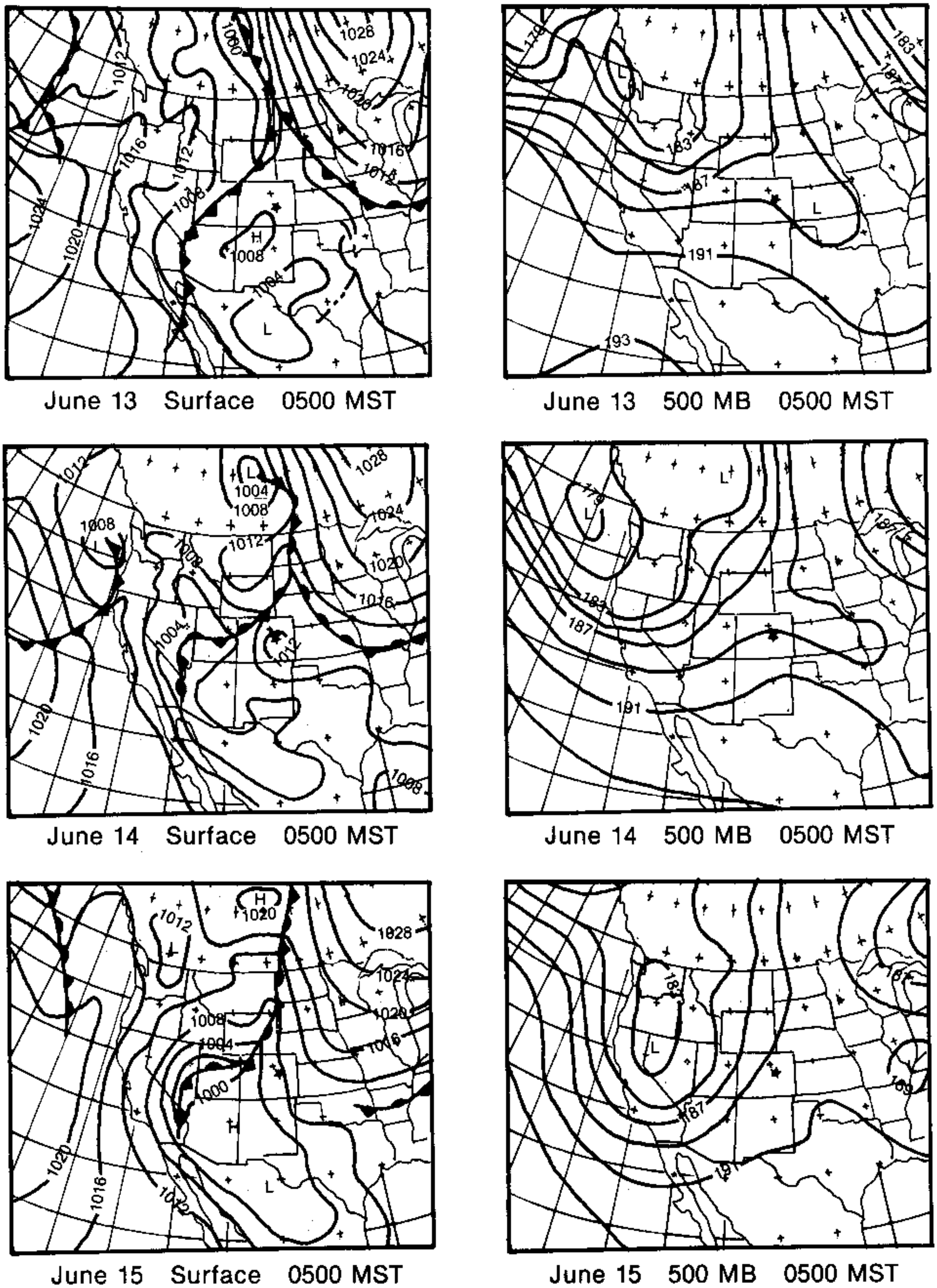


Figure 2.15.--Synoptic surface weather maps and 500-mb charts for June 13-15, 1965 - the Plum Creek, CO storm (76).

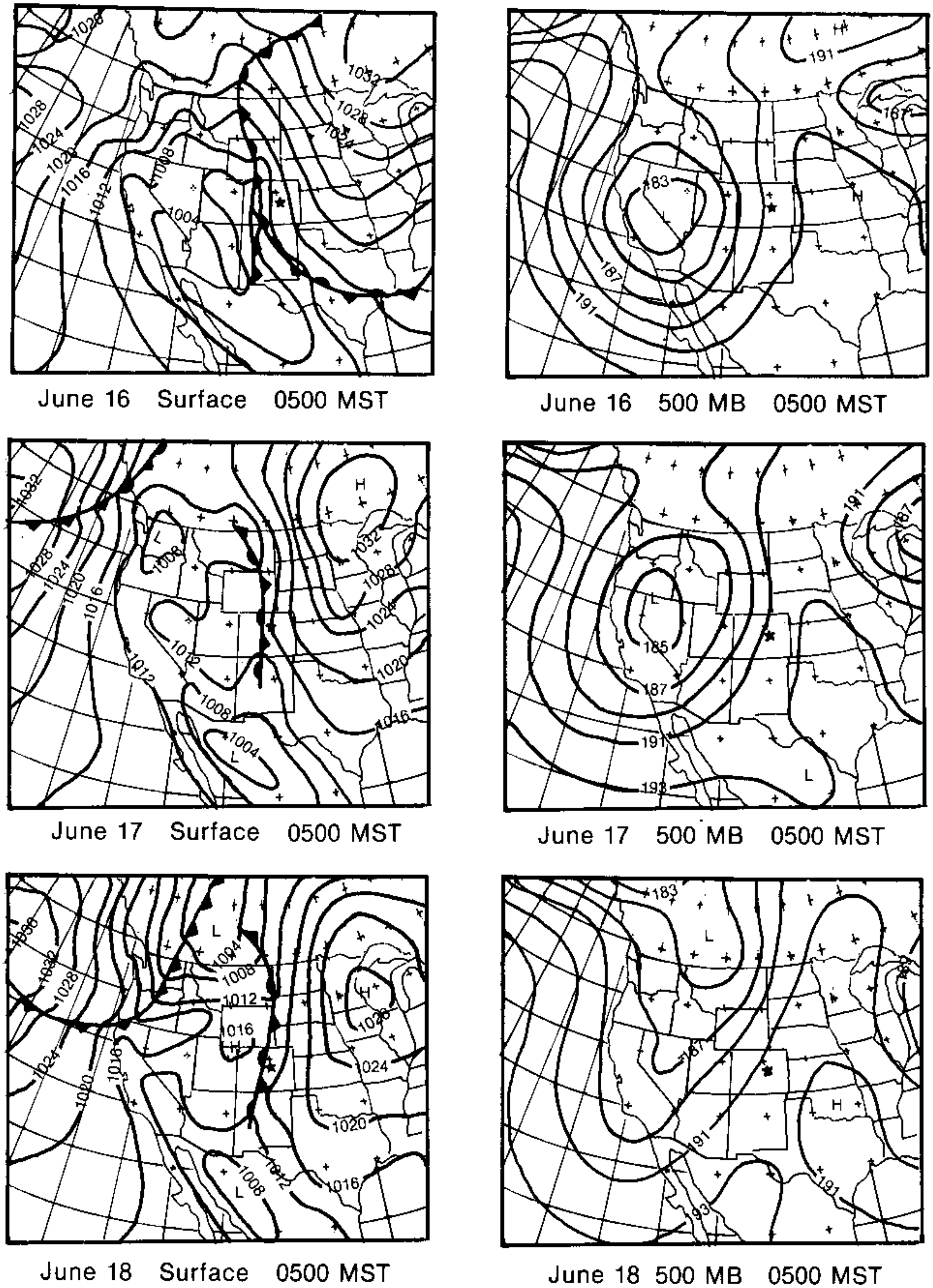


Figure 2.16.--Synoptic surface weather maps and 500-mb charts for June 16-18, 1965 - the Plum Creek, CO storm (76).

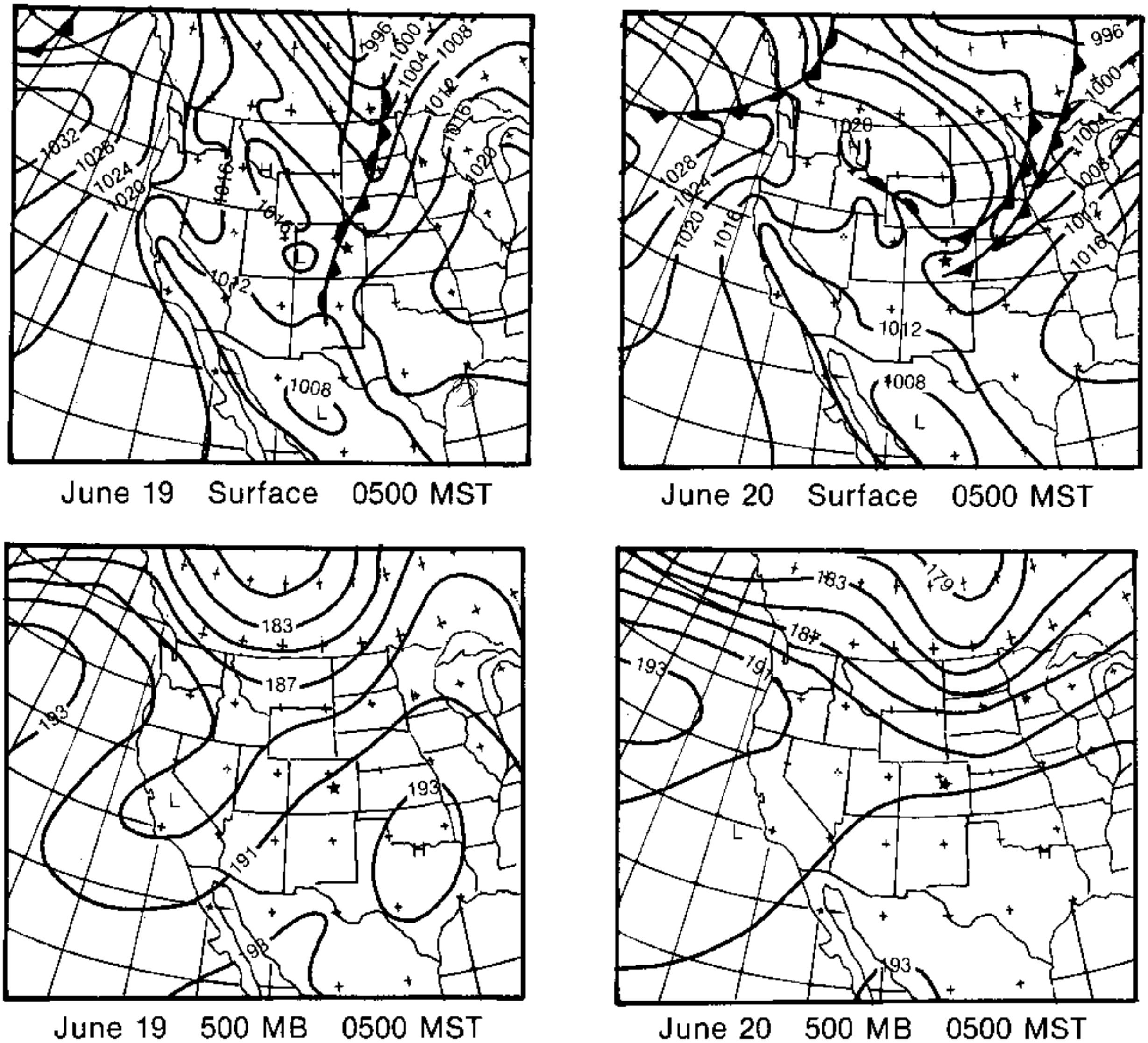


Figure 2.17.--Synoptic surface weather maps and 500-mb charts for June 19-20, 1965 - the Plum Creek, CO storm (76).

observation network, lines of severe storms were probably present in Colorado on all days during this storm period. During the afternoon of the 16th and into the 17th, rainfall became excessive over much of eastern and southeastern Colorado. Rainfall amounts of over 5 in. were common in the storm area for the 24-hr period ending in the late afternoon of the 17th. Extreme rainfalls reported by the State Engineers Office, USBR, and COE, showed rainfall amounts up to 14 in. in Douglas County on the 16th and in Elbert County on the 17th. A total storm isohyetal map is shown in figure 2.19. Other extreme amounts reported included 6 in. in 4 hr in El Paso County on the 17th and 6 in. in 30 min in Elbert County on the 15th. The 14-in. values on the 16th were estimated to have occurred in a few hours.

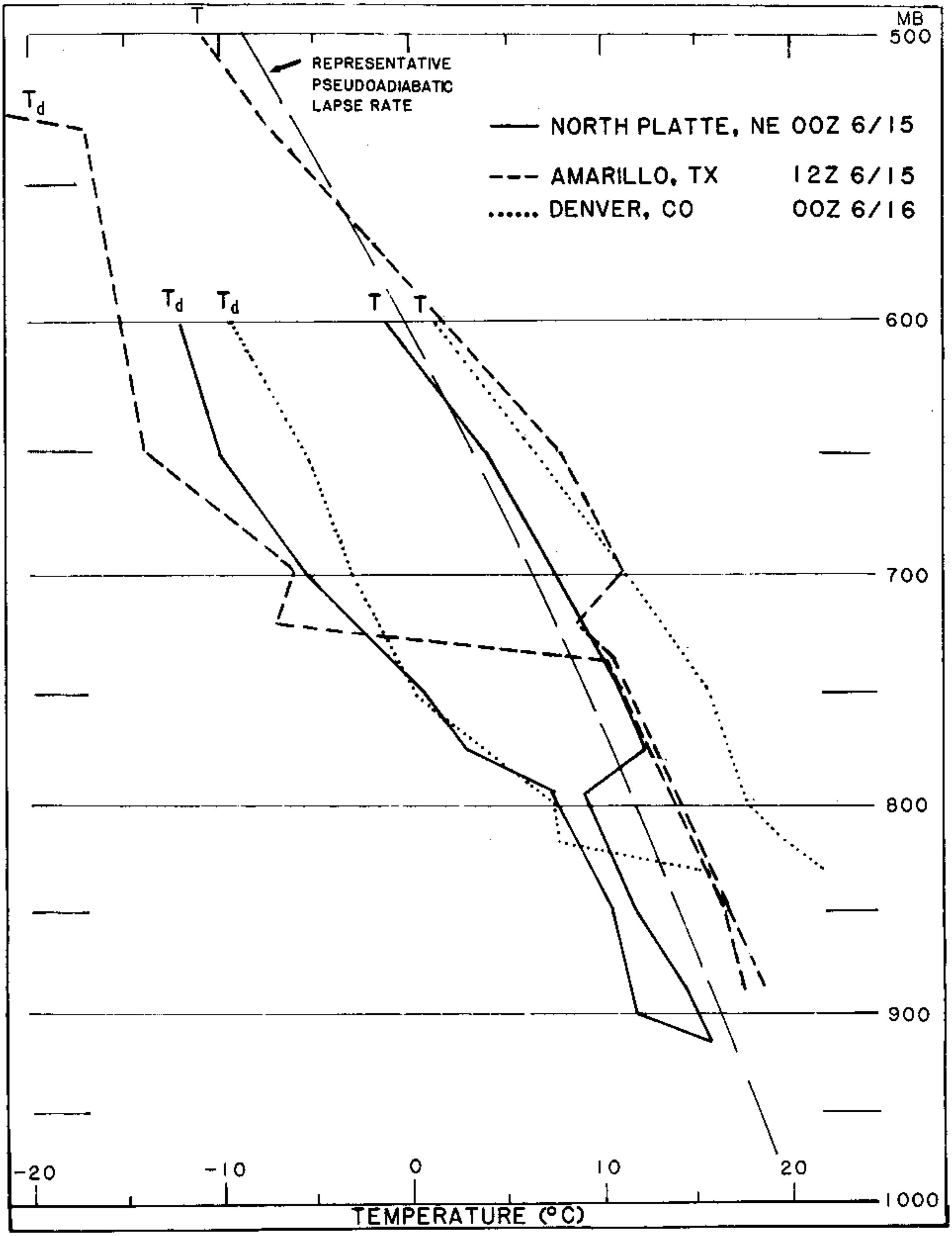


Figure 2.18.--Representative radiosonde observations for June 15-16, 1965 - the Plum Creek, CO storm (76).

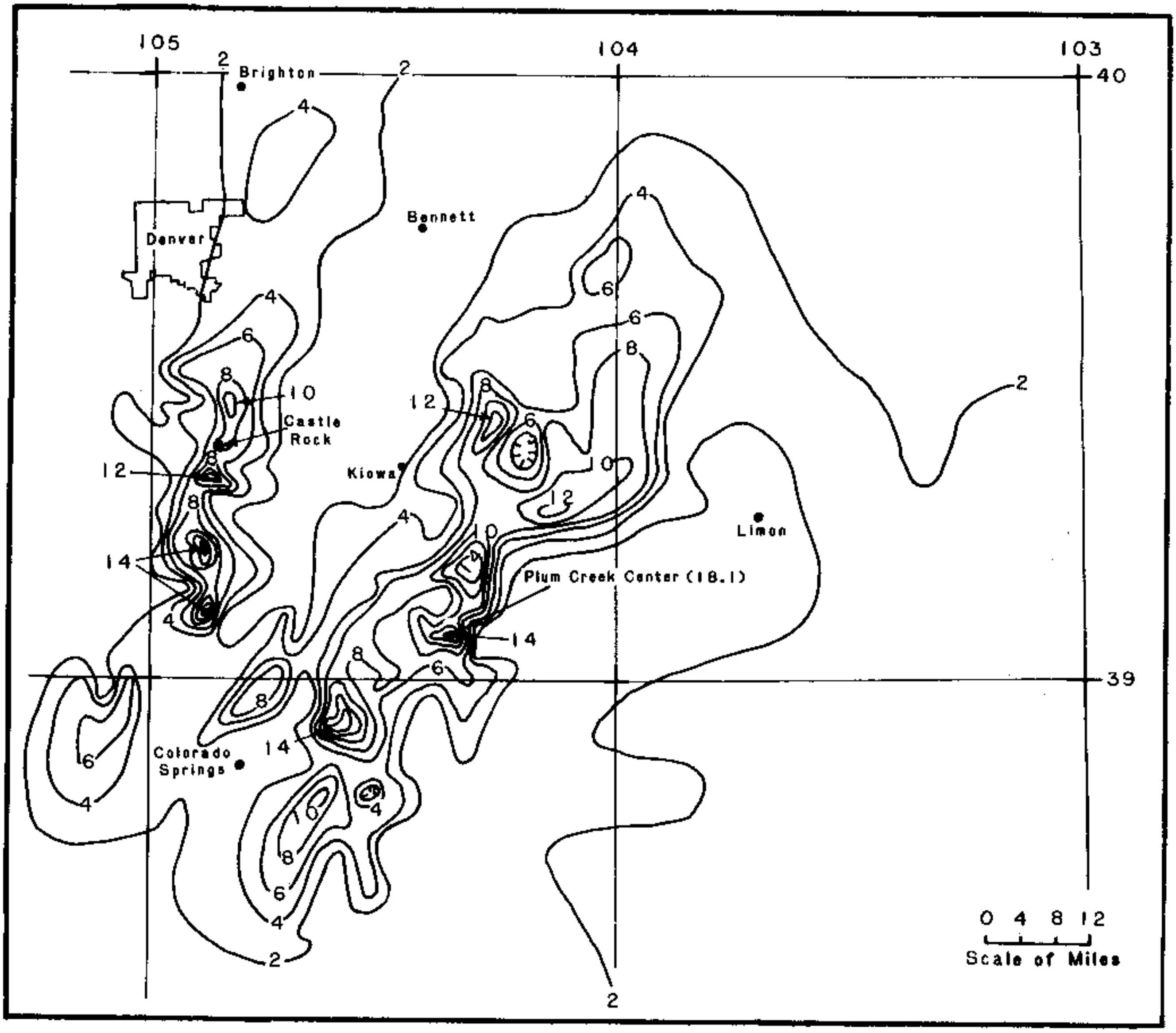


Figure 2.19.--Isohyetal map for June 16-17, 1965 - the Plum Creek, CO storm (76).

Convective storms became less prevalent after the 17th. Movement of the high pressure center to the southeastern United States reduced the strength of moist air inflow into Colorado, and allowed the cold front to move slowly to the east. This cold front weakened over the Plains States; however, severe weather was still reported over portions of the Midwest on the nights of the 20th and 21st.

Reduction in rains over eastern Colorado was also signaled by the weakening of the closed Low aloft on the 18th. This weakening also greatly reduced the inflow of moisture into the air column over eastern Colorado. By late afternoon on June 19 upper air flow over Colorado had become westerly.

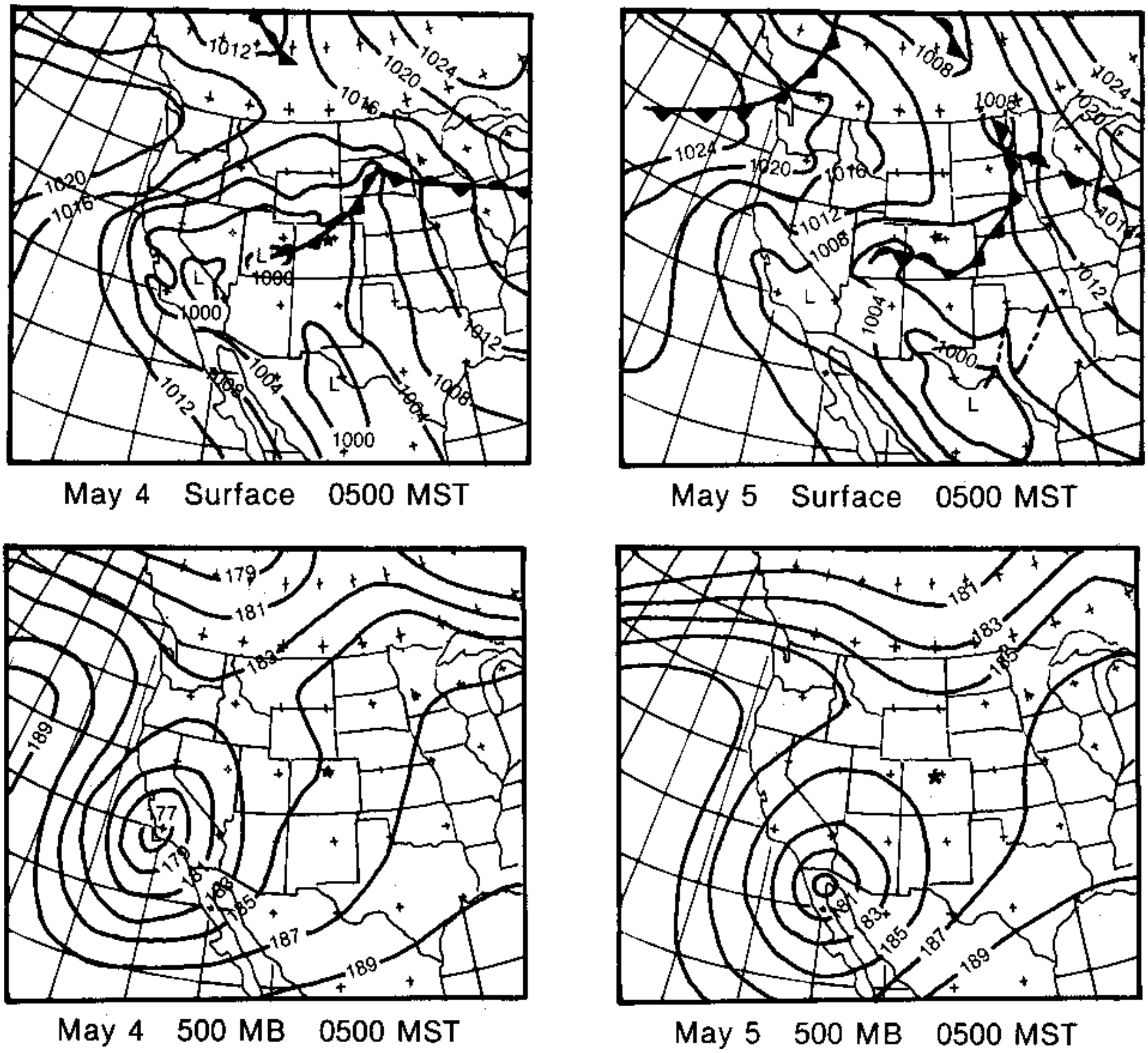
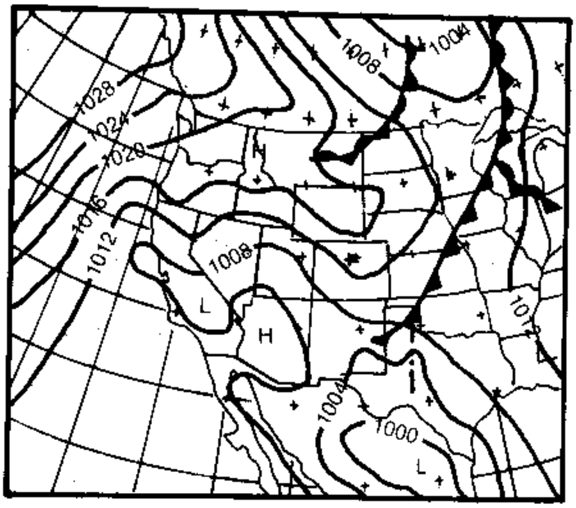


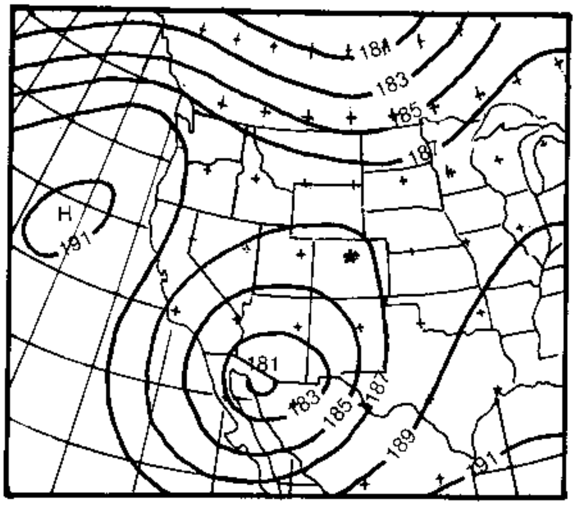
Figure 2.20.—Synoptic surface weather maps and 500-mb charts for May 4-5, 1969 - the Big Elk Meadow, CO storm (77).

2.4.1.8 Big Elk Meadow, Colorado - May 4-8, 1969 (77). Beginning on the afternoon of May 4, 1969, general rains began to fall over the first upslopes of the Rocky Mountains. The rain continued until the early morning of May 8, finally halting around 11:00 a.m. Rainfall was heaviest in a band from about 25 mi southwest of Denver northward to Estes Park.

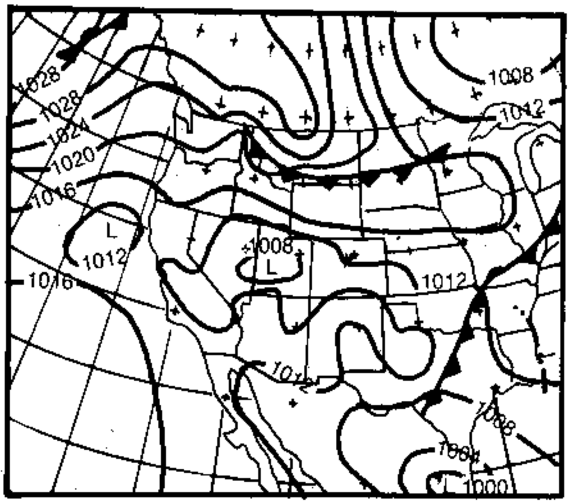
The surface and upper air weather patterns for the storm period are shown in figures 2.20 to 2.21. Early in the storm a persistent southeasterly flow from the Gulf of Mexico transported moist air into Texas, Colorado, and the Plains States. This flow was a result of a High near the mid-Atlantic coast and a weak Low center over northern Mexico at the surface. Aloft, a ridge was present over the Atlantic coast with a closed Low over the southwest. This circulation is conducive to drawing air from over the Gulf of Mexico and transporting it northward and northwestward. A weak cold front and Low were also present in Colorado when rain began on the evening of the 4th. Initial rains were probably the result of the warm moist air being forced over the cold front. It appears



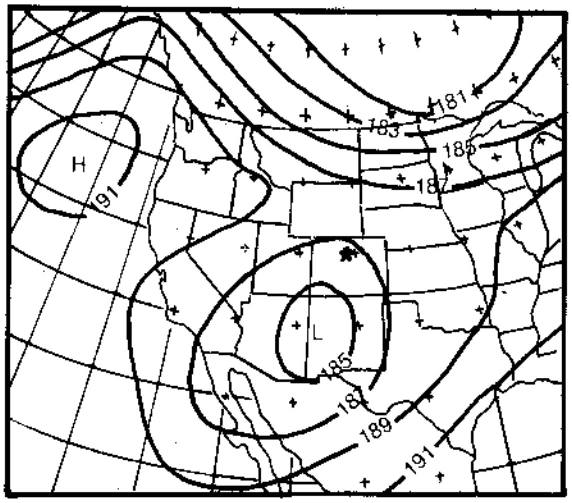
May 6 Surface 0500 MST



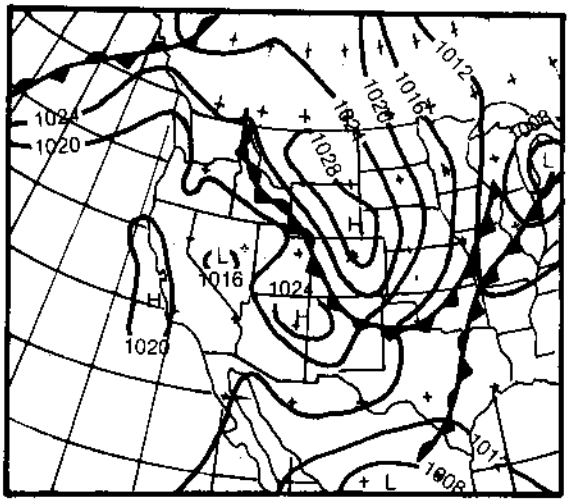
May 6 500 MB 0500 MST



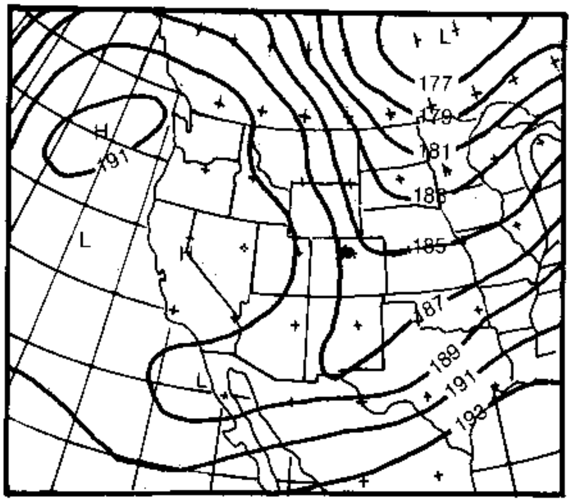
May 7 Surface 0500 MST



May 7 500 MB 0500 MST



May 8 Surface 0500 MST



May 8 500 MB 0500 MST

Figure 2.21.--Synoptic surface weather maps and 500-mb charts for May 6-8, 1969 - the Big Elk Meadow, CO storm (77).

the importance of the cold front diminished as it drifted slowly to the southeast. Orographic lifting, resulting from northeasterly flow across the Plains and onto the Rocky Mountains, became increasingly important during the storm period. This flow was a result of a High building to the north in the Montana-Dakota region beginning on May 5. As the High became stronger and the cold front moved further to the southeast, the easterly component of the flow behind the front and across Colorado became stronger. This brought the moist air already over the Midwest to the first upslopes. As the air was lifted by the mountains, the rainfall became more intense. The flow became strongest and the rainfall heaviest during the 6th and the 7th. Winds at the surface were predominantly from the east across Colorado and nearly normal to the mountains. The formation of a weak wave along the cold front in southwest Missouri on the 7th, probably served to reinforce the easterly component of the flow.

This pattern persisted until late on the 7th when a second cold front, with a High to the north, began pushing southward toward the storm area. This cold front brought northerly flow and colder, drier air behind it. As the front moved through Colorado on the night of the 7th and the morning of the 8th, it displaced the moist Gulf of Mexico air. This change in air mass stopped the rainfall over the Colorado region by midmorning of the 8th.

The consistent nature of these rains is evidenced by the hourly precipitation record. These data show that the rainfall, once started, continued throughout the storm with very few breaks. Near Boulder, CO, rainfall was first reported on May 4, at 11:00 p.m. After that, rainfall amounts were recorded nearly every hour until 8:00 p.m., May 7th, for a total of 69 hrs of recorded rain. The rainfall was very steady over this time period. Most available hourly reports show 1-hr rainfall maximums to be less than 1 in. This suggests that convective instability was not present, but rather that the rain was the result of a consistent lifting caused by the flow against the mountain. An isohyetal analysis of the storm (fig. 2.22) shows centers to be located along the first upslopes. As in most major storms, the largest amounts were determined by a "bucket survey" over the storm area. The survey yielded many reports of 10 in. or more. The largest total storm report of 20 in. was located at Big Elk Meadow Resort (40°16'N 105°25'W). Several other locations received amounts up to approximately 15 in.

2.4.1.9 Big Thompson, Colorado - July 31-August 1, 1976 (81). Disaster struck in the form of severe flash flooding east of Estes Park in the canyon section of Larimer County in north-central Colorado on the night of July 31, 1976. The flood took the lives of 139 people and caused many millions of dollars in property damage. The greatest loss of life occurred in the Big Thompson Canyon where campers were swept away by the "wall of water" tumbling through the narrow canyon.

The Big Thompson storm has been well documented by several authors. Details on particulars, such as precipitable water, dew points, radar summaries, etc., are provided by McCain et al. (1979), and Caracena et al. (1979). The following storm description is summarized from these sources.

The flash floods were a result of a complex system of thunderstorms that had begun to develop over the Colorado-New Mexico region on the afternoon of July 31. The storms formed in the humid Gulf of Mexico air that had circulated around a double frontal system extending from eastern Colorado eastward into

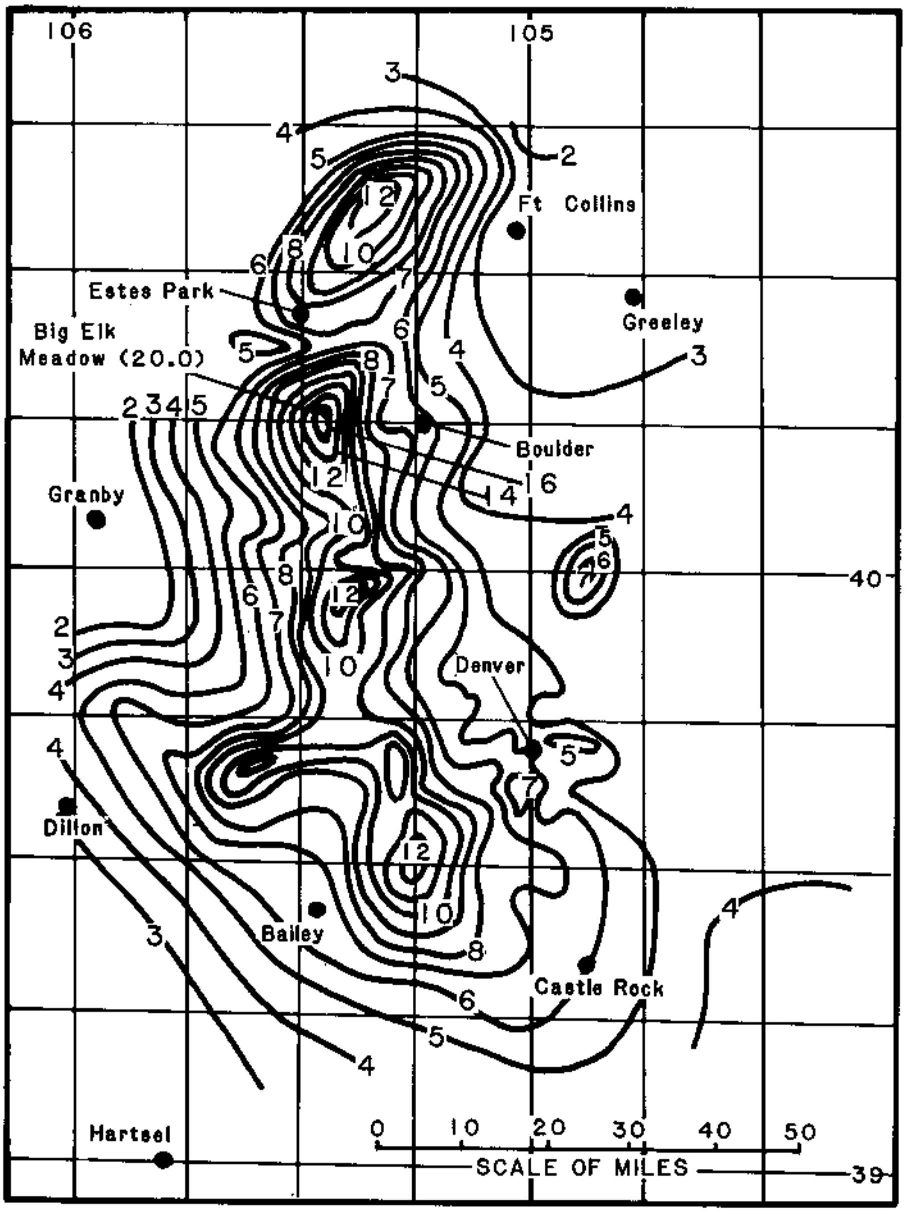


Figure 2.22.--Isohyetal map for May 4-8, 1969 - the Big Elk Meadow, CO storm (77).

Kansas (fig. 2.23). Weak pressure gradients at the surface probably contributed to the quasi-stationary nature of the fronts in Colorado. The fronts were very close together and can only be detected by an analysis that is more detailed than synoptic scale analysis. On the synoptic scale charts of figure 2.23 they are shown as a single front. For simplicity, in this report a single front will be used for reference.

Dew-point analyses over the south indicated that moist air had moved northward from the Gulf of Mexico and then turned with an easterly component of flow over the Plains States. This easterly flow carried the moist air to the front slopes of the Rocky Mountains in Colorado where it was lifted by both terrain and atmospheric processes. During the afternoon of the 31st, thunderstorms formed in several locations along the first upslopes of the Rockies and along the front

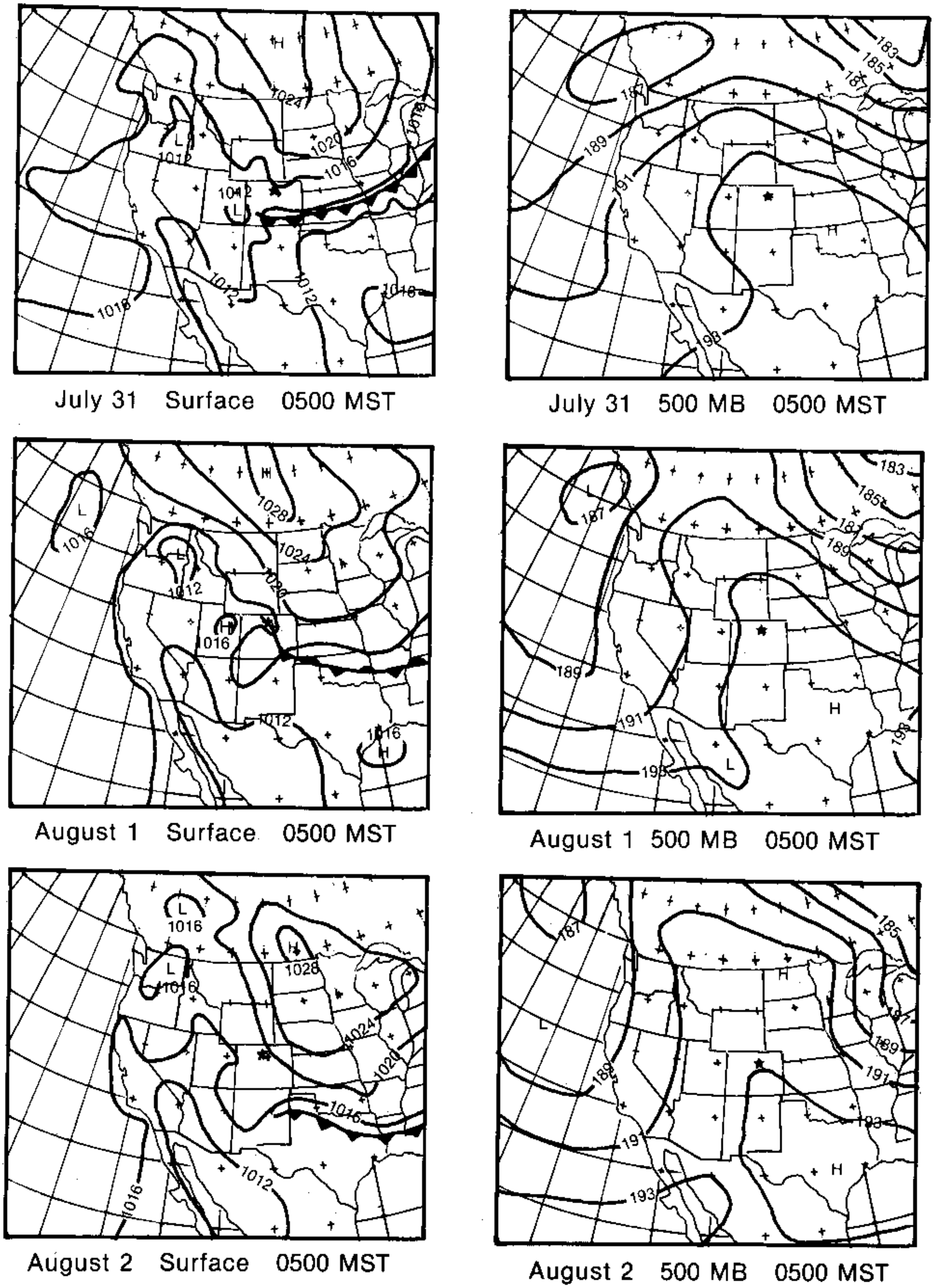


Figure 2.23.--Synoptic surface weather maps and 500-mb charts for July 31-August 2, 1976 - the Big Thompson, CO storm (81).

extending to the east. The timing of the growth indicates that insolation probably played a role in the development of the thunderstorms. Radar summaries and satellite pictures (not shown) indicate that the thunderstorms were growing rapidly and becoming locally intense in the Big Thompson area by 1700. Up to this time rainfall had been light and scattered over Colorado.

By 1730, rain had started over the Big Thompson basin. During the next 4 hr, heavy cloudburst-type rains fell in or near the Big Thompson basin as these severe storms remained nearly stationary over the area. Rainfall was heaviest from about 1830-2100. This was due to the apparent merging of storm cells over the area as depicted by radar summaries. Light winds aloft during the storm period also contributed to the severity of the storms by providing little entrainment of dry air from the surrounding upper levels. The light flow also permitted the storm cells to form and reform over nearly the same location. A short wave trough at 500 mb, moving north along the western edge of the ridge, was also making its way into the storm area during this time (fig. 2.23). This trough aloft probably enhanced the development of the thunderstorms, increasing their severity. Rainfall diminished over the Big Thompson basin around 9:30 p.m. on the night of July 31. Other heavy rainfall occurred between 11:00 p.m. and 3:00 a.m. on August 1 in areas to the north-northeast of the Big Thompson basin. These storms were not as severe as those over the Big Thompson basin. The heaviest precipitation occurred in a 10-mi-wide band from 8 mi south-southeast of Estes Park north-northwestward to the Colorado-Wyoming border. Maximum rainfall amounts of 12 in. of rain occurred between 5:30 p.m. and 9:30 p.m. July 31 (Miller et al. 1978). A point maximum of 12.5 in. in 4 hr (40°25'N 105°26'W, elevation 8,000 ft) has been accepted for this storm. The rainfall drops off quickly in all directions from the storm centers, exhibiting the local nature of the individual storm centers.

A storm isohyetal map is shown in figure 2.24. The map covers the most intense part of the storm and is for the maximum 4-hr rainfall on July 31, 1976. It shows the amounts from the local thunderstorm cells that resulted in heavy flash floods.

2.4.2 Tropical Storms

The southern part of the study region, from the Mexican border to approximately 37°N, has been affected by the remnants of several tropical storms. Throughout this southern portion of the study region these storms are a major producer of heavy rainfall, and could be considered a prototype for the PMP storm.

2.4.2.1 Rancho Grande, New Mexico - August 29-September 1, 1942 (60). The rainfall during the Rancho Grande, NM storm was associated with a tropical storm which moved inland from the Gulf of Mexico on the morning of August 30. The circulation of the storm was still identifiable as it entered New Mexico. Large-scale convergence from the cyclonic motion was a primary mechanism causing the precipitation. Thunderstorm activity preceded and followed passage of the disturbance into New Mexico.

The storm originated as a tropical depression in the eastern Caribbean Sea near the Gulf of Venezuela on August 21, 1942. It strengthened while moving westward, and by the evening of August 24 achieved winds of hurricane force. The hurricane veered slightly at this time, taking on a west-northwestward movement. The hurricane crossed the tip of the Yucatan Peninsula during the night of

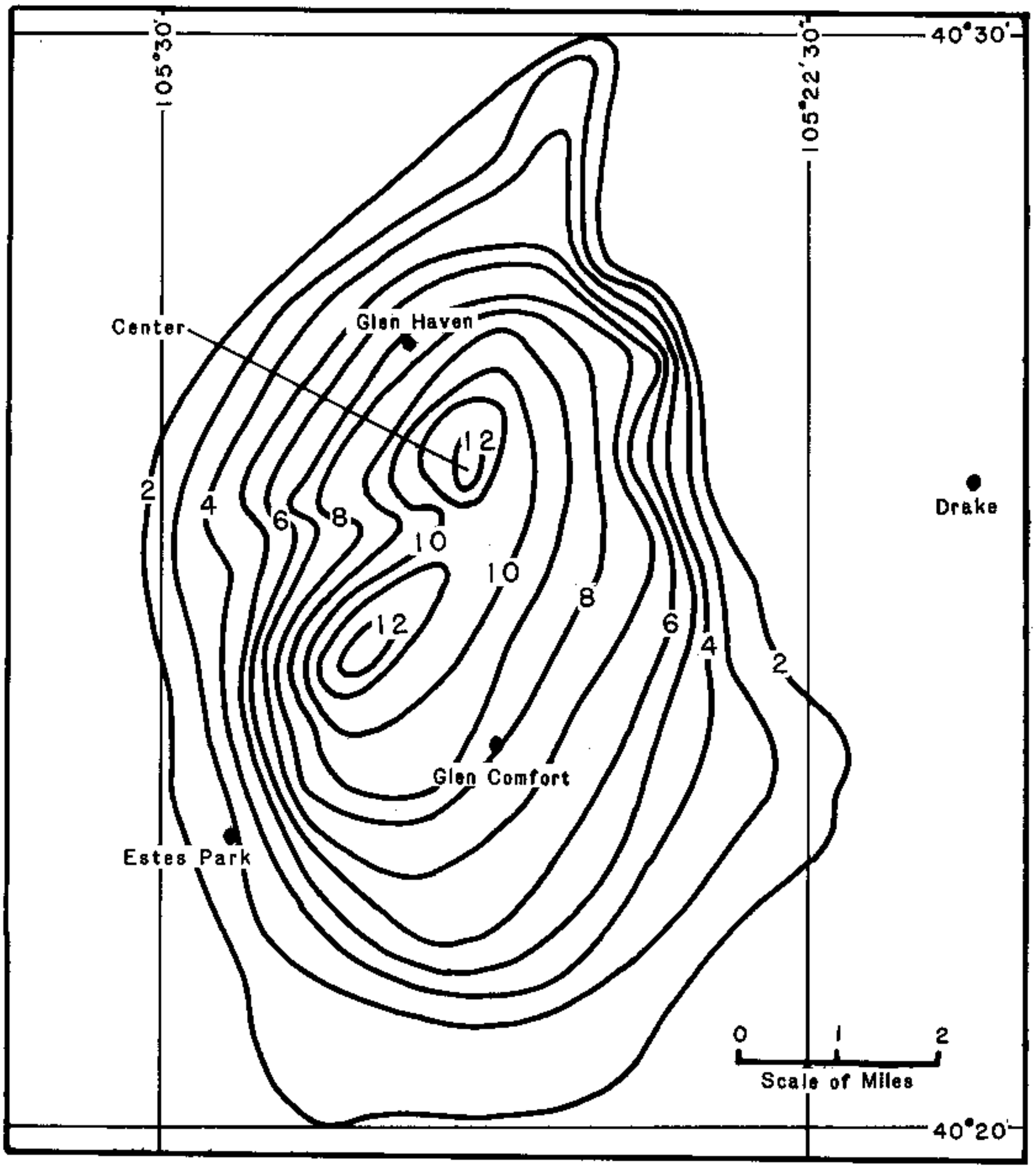


Figure 2.24.—Isohyetal map of intense 4-hr precipitation for July 31, 1976 - the Big Thompson, CO storm (81).

Mexico. By the morning of August 29, the surface winds along the Texas coast reflected the proximity of the approaching storm.

On August 29, a large maritime tropical air mass covered the eastern United States, while a polar mass of high pressure dominated eastern Canada. A weak Low was centered over the Great Basin and a polar air mass covered the Pacific northwest. During the afternoon of the 29th, thunderstorm activity began over eastern New Mexico as tropical air from the Gulf of Mexico was forced over the terrain. A few stations reported over an inch of rain by the end of the day. Thunderstorm activity decreased on the 30th, as the surface wind shifted to northeasterly under the influence of the tropical cyclone.

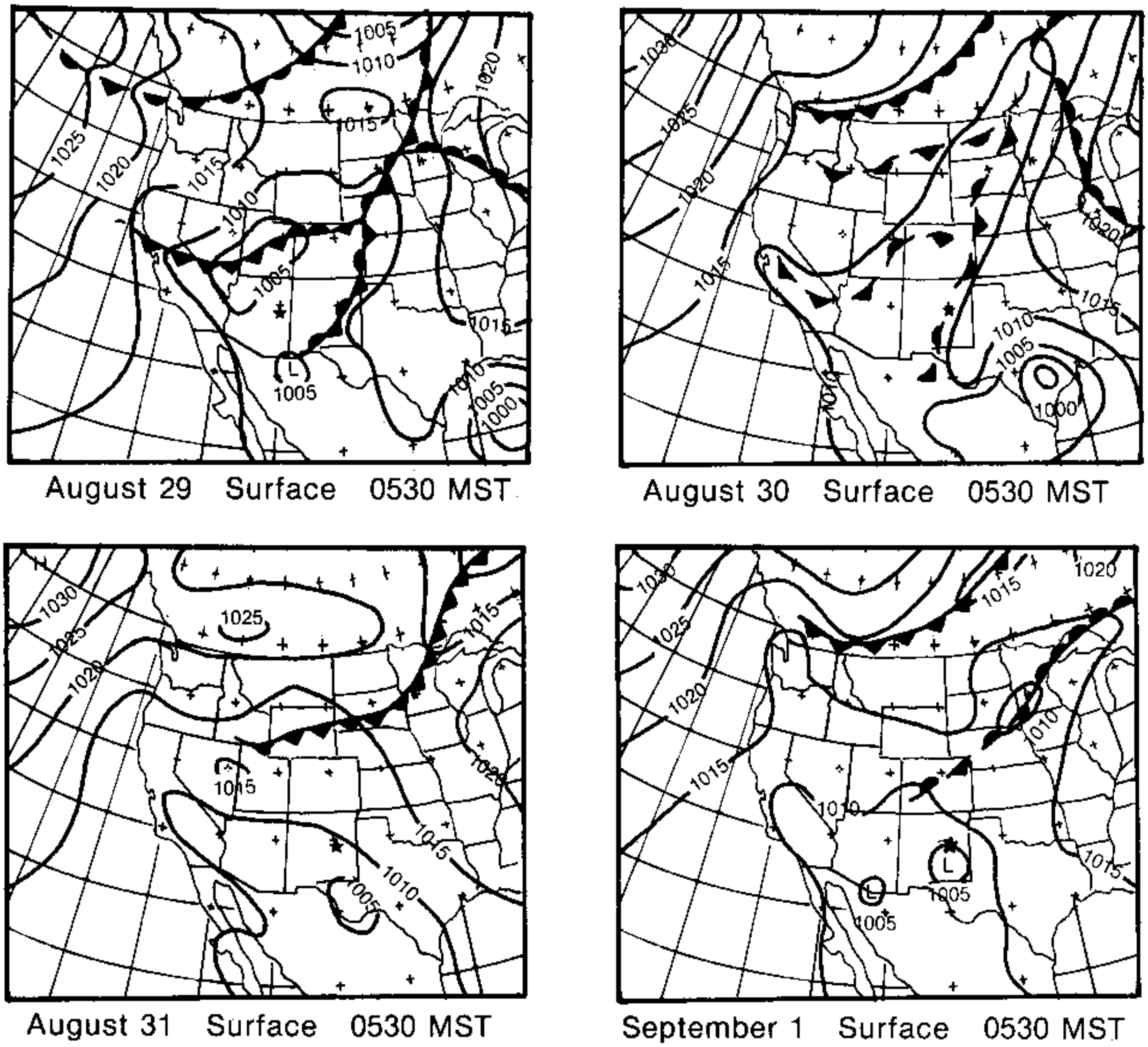


Figure 2.25.--Synoptic surface weather maps for August 29-September 1, 1942 - the Rancho Grande, NM storm (60).

The hurricane continued on the straight northwestward course and reached the Texas coast near Matagorda Bay slightly before 5:30 a.m. the morning of the 30th (fig. 2.25). Its movement remained northwestward at a speed of approximately 15 mph and its intensity decreased from hurricane strength to that of a tropical storm. The rain area accompanying the storm reached southeastern New Mexico late on the 30th and advanced steadily northward enveloping most of the lower Pecos Valley by the early morning on the 31st. The storm center itself entered New Mexico on the morning of the 31st and remained nearly stationary south of Roswell during the remainder of the day, with steady moderate rain north of the center. Late in the day, the storm began to move north-northeastward, steadily losing intensity. When it reached Tucumcari early on the following morning - September 1 - a cyclonic circulation was still evident. By this time rainfall had spread northward into southeastern Colorado and ended in the region south of an Albuquerque, NM - Amarillo, TX line. The final burst of rain in the storm consisted of scattered thunderstorms preceding and accompanying a cold front which approached from the north. The front moved across Colorado on September 1, and continued southward across Texas and New Mexico.

This storm was remarkable in that after traveling more than 700 mi over land, it still maintained a well defined strong cyclonic circulation, although no longer of hurricane intensity. Not a single station in the path of the storm reported thunder at the time of the heavy rain, indicating that large-scale convergence rather than local convection was the principal cause of precipitation.

The maximum precipitation for the 84-hr storm was 8.0 in. at three sites: Rancho Grande, Maxwell, and Chico, NM (fig. 2.26). The 2-in. isohyet encompassed over 35,000 mi^2, most of which was in the state of New Mexico. The maximum average depth of rainfall over a 1,000-mi^2 area for 24 hr was 6.8 in. The isohyetal analysis for this storm showed an orientation of the rainfall pattern from south-southwest to north-northeast, approximately paralleling the track of the storm and the mountain ranges.

2.4.2.2 Vic Pierce, Texas - June 23-28, 1954 (112). The depth of precipitation reported at Vic Pierce, TX for 10 mi^2 and 24 hr was 26.7 in. Precipitation from this storm was a direct result of the movement of Hurricane Alice from the Gulf of Mexico up the Rio Grande Valley. Heaviest rains occurred about 90 mi northwest of Del Rio, TX, during the period when the storm was losing its warm-core tropical storm structure.

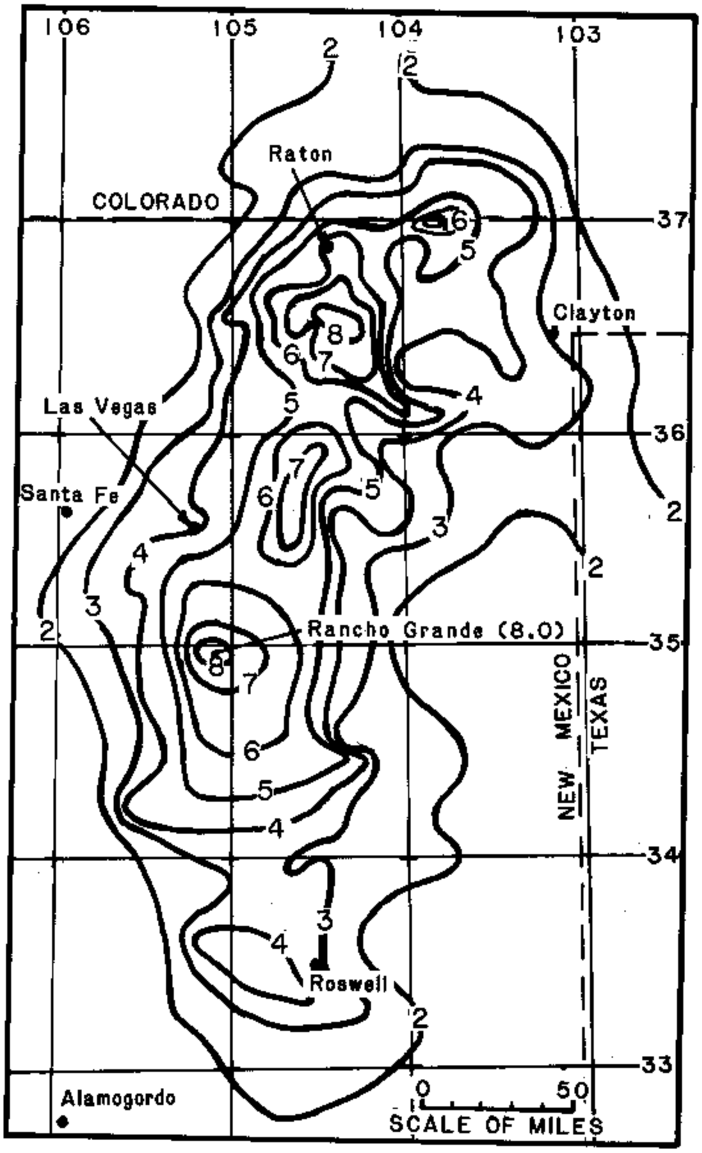


Figure 2.26.—Isohyetal map for August 29-September 1, 1942 - the Rancho Grande, NM storm (60).

On June 24, 1954 (fig. 2.27), a small hurricane in the western Gulf of Mexico 300 mi southeast of Brownsville was discovered by ship personnel. This hurricane, named Alice, moved from its birthplace on a track toward the northwest typical for this season and region. The storm crossed the coast some 50 mi south of the mouth of the Rio Grande, at about noon on the 25th (fig. 2.27), and proceeded up the short distance south of Brownsville, Larado and Del Rio, TX. The surface wind at Brownsville rose to nearly 50 mph while a pilot balloon measurement of wind speeds aloft showed a speed of 130 mph from the southeast at 3,500 ft. As the center passed Del Rio at noon on the 26th, the highest surface wind was 33 mph (the fastest single mile of wind). The low-level

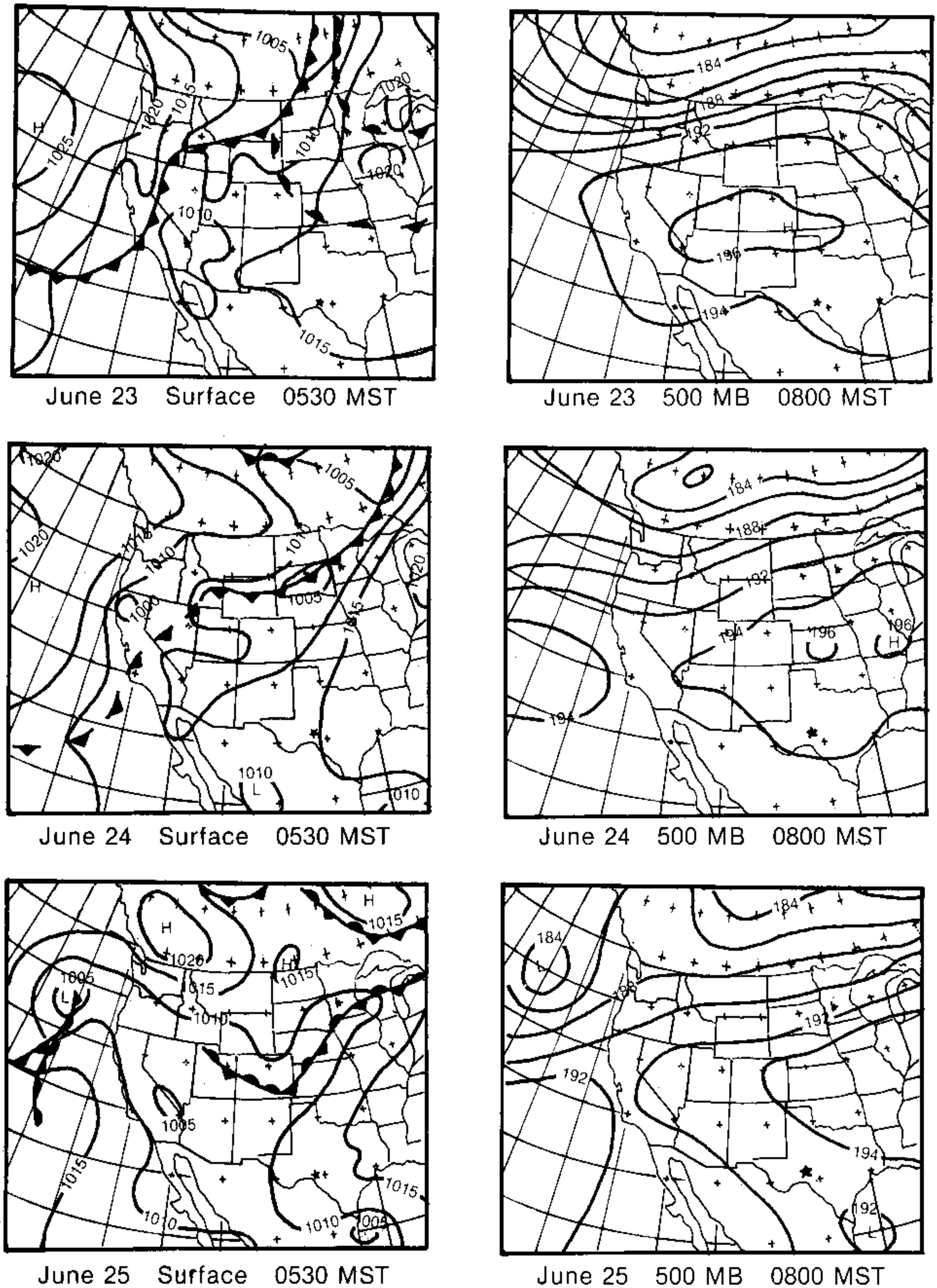


Figure 2.27.--Synoptic surface weather maps and 500-mb charts for June 23-25, 1954 - the Vic Pierce, TX storm (112).

jet winds also diminished. The highest speed revealed by the 8:00 a.m. pilot balloon observation was 48 mph at 3,000 ft above sea level. However, the storm on this day still maintained its warm core as evidenced by the 500-mb temperature at Del Rio.

Continuing on its northwestward track, the storm crossed the Rio Grande to the region between the Big Bend of the Rio Grande and lower Pecos River. It stalled there during the night of the 26th and remained nearly stationary through the 27th. Early on the 28th (fig. 2.28), the storm remnants were barely discernible as a cyclonic wind circulation with a weak low pressure center. At this time it began to move across the lower Pecos River and finally lost its identity in north Texas. After it passed Del Rio, the cyclonic circulation of the storm was more distinct at 5,000 ft than at the surface. This is typical of decadent hurricanes. The storm was further identified at 5,000 ft by the temperature at the core of the disturbance which, by that time, was some 4°C colder than its surroundings. The warm anticyclone aloft and at the surface was quite strong and persistent from Florida across the Gulf Coast States into New Mexico while the storm was moving up the Rio Grande Valley. There were some weak indications in the 500-mb wind field that the storm interacted with a wave in the westerlies extending south from Montana as it was producing the record rainfall northwest of Del Rio.

During the progress of the storm over the relatively flat country of the Rio Grande Valley below Del Rio, rains were only moderate for a hurricane. In Texas, there was a 6-in. center at Hebronville, about 130 mi northwest of Brownsville, TX, and another center in excess of 6 in. near Uvalde, about 270 mi northwest of Brownsville. Stations along the Rio Grande experienced total precipitation ranging from a fraction of an inch to 4.5 in. (fig. 2.29). In Mexico, south of the storm track, precipitation was very light. Northwest of Del Rio, some orographic effect was apparent in the reported precipitation amounts. The storm encountered the steepest slopes of the narrowing valley of the Rio Grande between the Serranias del Burro in Mexico and the tip of the Balcones Escarpment in Texas. The first of the very heavy rains, near Langtry, TX, however, began as the center of the decadent hurricane arrived there. Detailed information on the wind flow is lacking, but it is reasonable to suppose that the prevailing flow into the area of heaviest rain was from the southeast.

Several hours after the passage of the hurricane center, the rain at Langtry slacked off and stopped altogether soon after noon on the 27th. The principal activity then shifted 30-60 miles north, to the region between Pandale and Ozona, TX. A succession of thunderstorm cells released very heavy rains along this axis for as long as the center of the transforming hurricane was located a short distance to the west of the axis. The precipitation ended over this region only after the storm center moved to the north. There are two rainfall centers shown on the isohyetal analysis at which the total accumulated precipitation for the storm, according to unofficial measurements, was 35 in. The location of one (Everett) is in a saddle near the Pecos River at the head of a general slope up from the south, 1,700 ft above sea level. The other (Vic Pierce Ranch) is near a rim of a plateau at an elevation of 2,200 ft.

The heavy rains are most closely related to the stalling of the northwestward movement of the hurricane remnants while it was transformed into a cold-core system when interacting with a weak wave in the westerlies. Although the overall precipitation pattern can be associated with the generally southward-facing

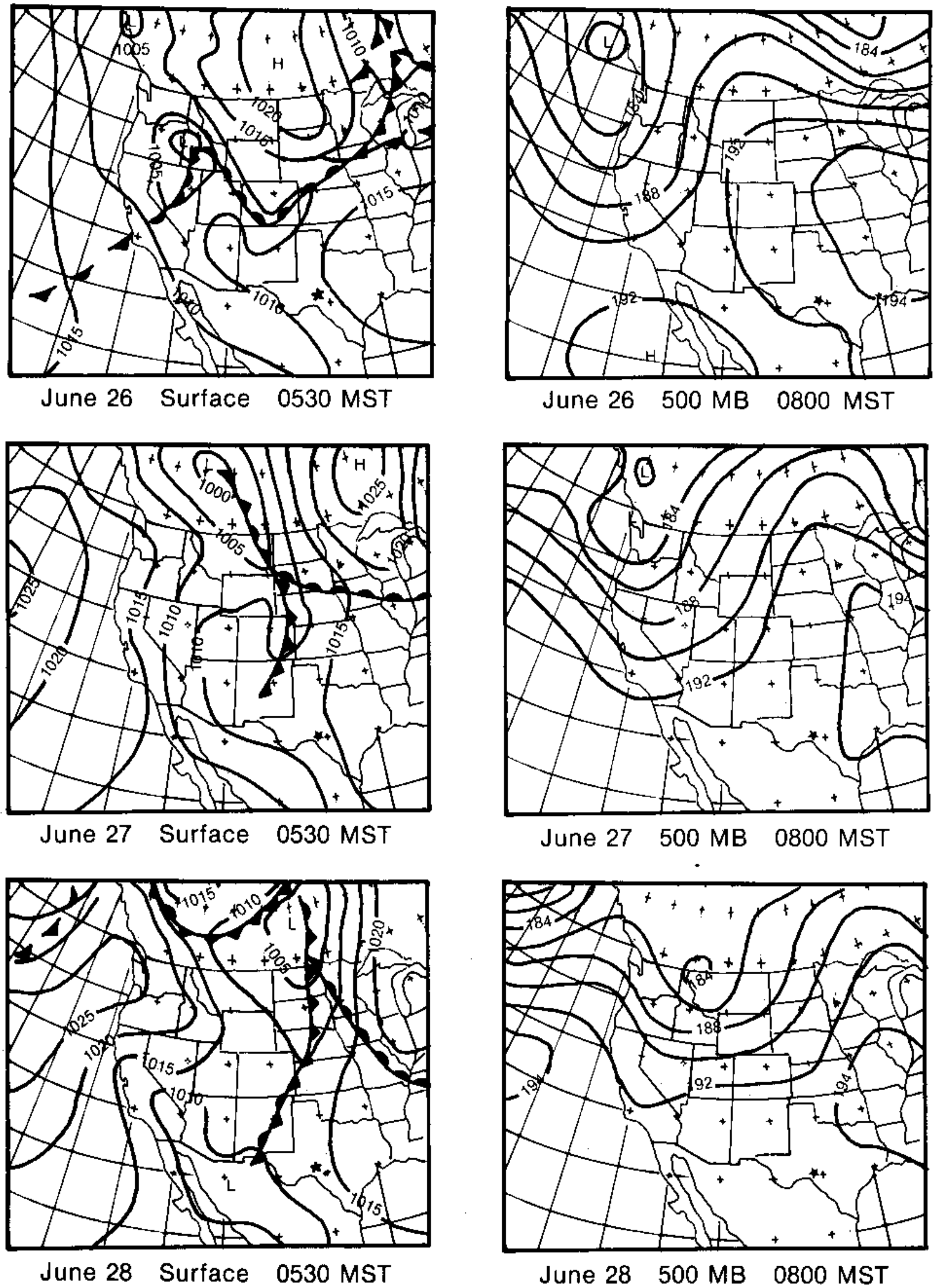


Figure 2.28.--Synoptic surface weather maps and 500-mb charts for June 26-28, 1954 - the Vic Pierce, TX storm (112).

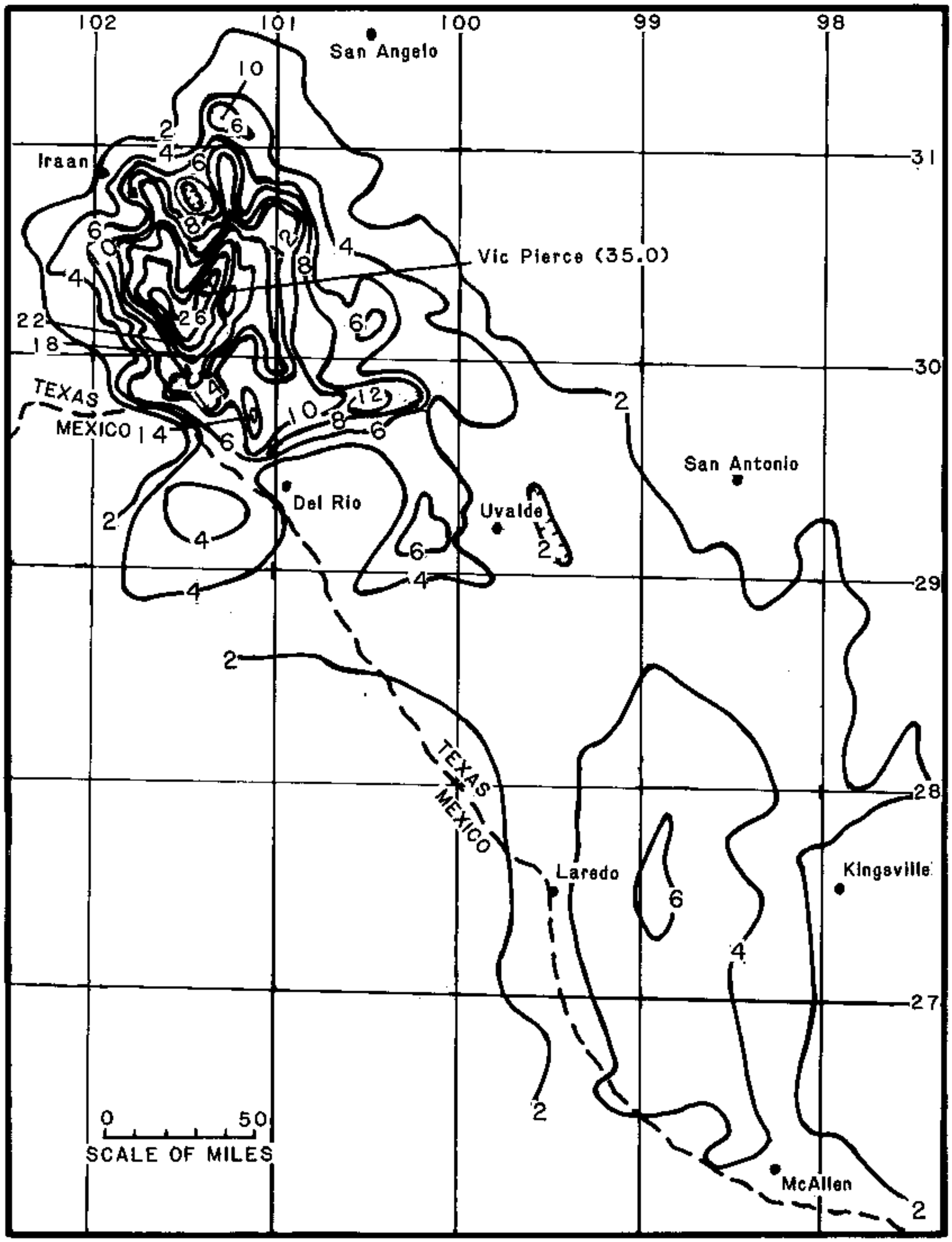


Figure 2.29.--Isohyetal map for June 24-29, 1954 - the Vic Pierce, TX storm (112).

slopes of the Edwards Plateau in the area northwest of Del Rio, specific isohyetal maxima and minima appear poorly correlated with places where the slopes are most pronounced.

2.5 Storm Classification

One objective of a comprehensive study of the meteorological situations surrounding major storms is the development of a classification or grouping system. The system may then be used to determine in which regions similar storms have occurred. Once these regions have been decided, transposition limits for individual major storms can be more easily determined. The system was developed from the study of the major rain storms in the region, some of which have been discussed in section 2.4.

2.5.1 Storm Classification System

Development of a storm classification system, based upon the factors most important for occurrence of an extreme rainfall event, is complicated by the existence of more than one factor that can be assigned in most storms. In the system developed, only one factor can be assigned to each storm. The first separation is between general cyclonic and convective storms. Within the convective storm grouping, storms are further subdivided into complex and simple systems. Within the cyclonic storm classification, the storms are grouped into tropical and extratropical storms. The extratropical storms are further classified as those in which the precipitation results primarily from frontal action and those in which the precipitation results primarily from convergence around a low pressure system.

2.5.1.1 - Characteristics of Storm Classes. Convective precipitation is caused primarily by vertical motion within an extended mass of air where the air is warmer than its environment. Convective precipitation is usually limited in areal extent and of relatively higher intensity, and produces greater amounts over smaller areas than that resulting solely from large-scale cyclonic activity. Convective storms are sometimes accompanied by thunder. Frequently in these storms, periods of intense rainfall are separated by periods of little or no precipitation. The fundamental unit is the storm cell. Diameter of this mass of air is about 10 mi or less and typically forms a single cumulonimbus cloud. The affected area is greater when a group of related convective events are considered together.

The classification system includes both simple and complex convective storms. Simple convective storms are those isolated in both time and space. The duration is usually less than 6 hr and the total storm area is generally less than 500 mi^2. When precipitation is caused by a group of simple convective storms, the event is classified as a complex convective storm. Generally the duration will be longer than 6 hr and the total storm area will be greater than 500 mi^2. It should be remembered that, in a complex convective case, the total duration of all storm events combined is less than 24 hr, and the total storm area, generally, is only a few thousand square miles.

Cyclonic precipitation is primarily caused by the large scale vertical motion associated with synoptic scale weather features such as pressure systems and fronts. The vertical motion is related to the horizontal convergence of velocity near the surface. The extent of the total storm area, as reflected by the isohyetal pattern, is typically larger than 10,000 mi^2. The total duration of the storm is one or more days. The precipitation is steady rather than high intensity bursts or showers.

The distinction between an extratropical and tropical cyclonic storm is in the location of storm origin. While extratropical storms originate at a latitude greater than 30°N, tropical storms all originate in a latitude band between 5°N and 30°N. Tropical storms affecting the CD-103 region originate in either the Gulf of Mexico, the Caribbean Sea or the Atlantic Ocean. Adequate supplies of both real and latent heat are necessary conditions for the formation of tropical storms. These conditions are met over the three tropical regions mentioned. In this study, only those storm events are included as tropical cyclones where the precipitation can be attributed to a tropical storm circulation, or where the track of the center of moisture can be matched with storms found in "Tropical Cyclones of the North Atlantic Ocean - 1871 - 1980" (Neumann et al. 1981).

Rainfall events from cyclonic storms of extratropical origin can be further subdivided into those resulting from circulation around low pressure centers and those associated with frontal systems. The rainfall associated with low pressure centers results from cyclonic flow close to the surface over an area near, and generally to the north of, the low pressure center. The low pressure center is generally moving eastward through the area of concern. The effective storm duration is generally about three days. Generally, cold fronts cause most of the extreme rainfall associated with frontal systems in this region. Such a front represents the leading edge of a mass of cooler air moving from northwest to southeast through the region. The heaviest precipitation is associated with the cold front as it passes through the region. The associated low pressure system is at least 100 mi from the precipitation center. Precipitation generally is of shorter duration than that associated with low pressure centers.

The descriptions in the previous paragraphs present idealized situations. Most storms result from a variety of causes. Since the adopted procedures allow only one classification to be assigned to each storm, a method has been developed to select the appropriate type when various causative factors are present. The storm is examined in terms of the total precipitation volume. The percentage of this volume contributed by each storm type is estimated. The storm type contributing the greatest percentage is used as the basis for storm classification. Simple convective storms cannot occur in combination, or as a portion of other storm types. In some portions of the region, these storms provide the maximum precipitation amounts for short durations and small areas. Outside these regions, combinations of convective and cyclonic types can occur. When determining the duration as discussed in the various storm types, an effective storm duration is used. This duration is defined as the shortest period of time in which at least 90 percent of the total rainfall has occurred for the majority of the storm area. This is generally determined from pertinent data sheets from "Storm Rainfall in the United States" (U.S. Army Corps of Engineers 1945 -), hereafter referred to as "Storm Rainfall." The classification of the storm type is a step-by-step process in which a decision is made on the most general categories first. A second decision follows, and for some storm types a third decision is made. The schematic for classification of storms, figure 2.30, illustrates this process.

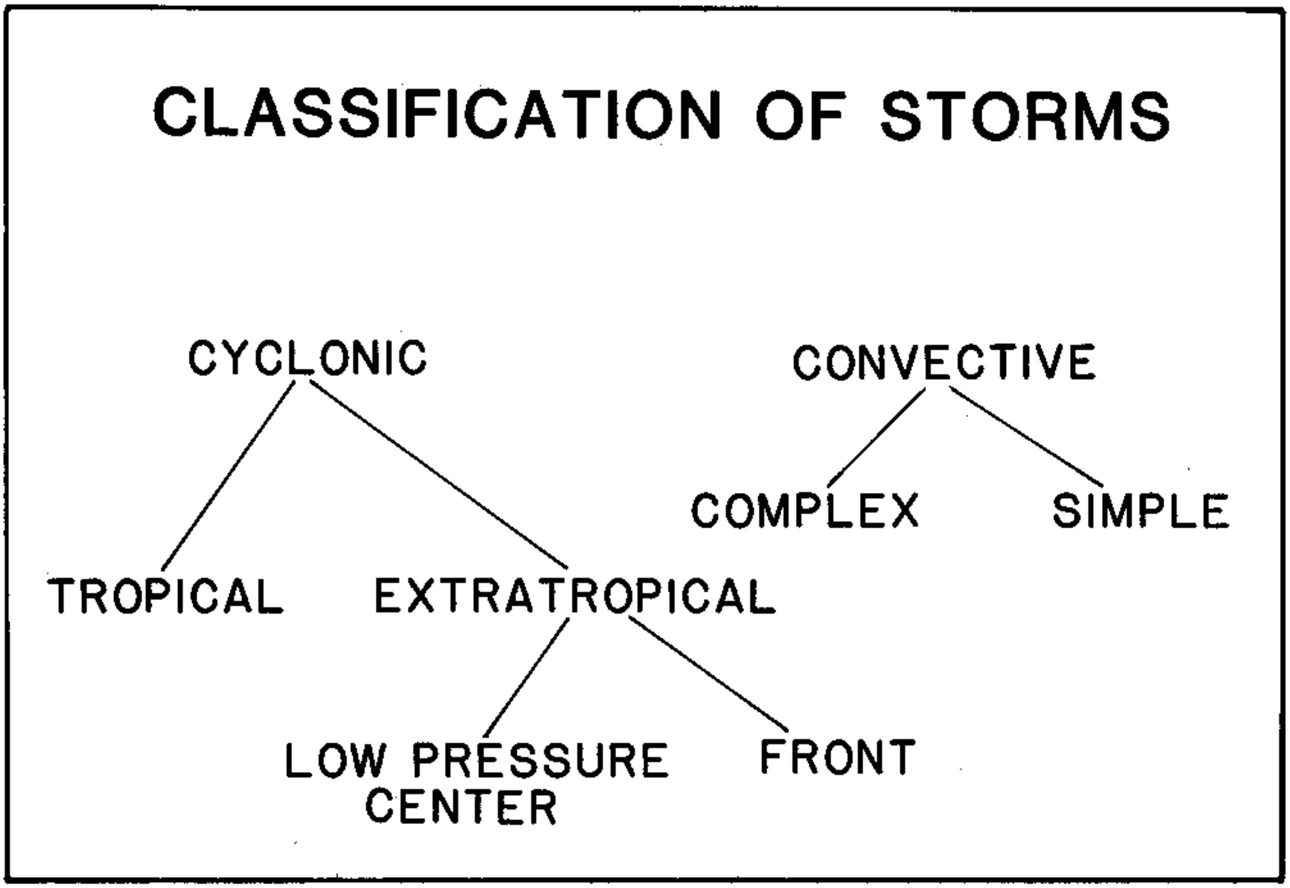


Figure 2.30.--Schematic illustrating the storm classification system.

2.5.2 Example of Application of Storm Classification System

The application of the storm classification system can be understood by examination of a particular important storm. The storm selected for this example was centered at Penrose, CO on June 2-6, 1921 (31).

2.5.2.1 Convective/Cyclonic. Five different criteria can be examined to classify a storm as cyclonic or convective. These are: 1) weather maps; 2) mass curves of rainfall; 3) isohyetal pattern; 4) effective storm duration; and 5) total storm area. An interpretive judgment will be made regarding each of these criteria.

The surface synoptic weather maps are examined for storm criteria. Figure 2.4 shows the weather maps for June 2-6, 1921. Although two cold fronts passed through the region during this storm period, one on June 1-2 and the other on June 5-6, their passage was not reflected by much rainfall. Most of the rain occurred on the night of June 3-4 at times when these fronts were at least 150 mi away. Low pressure centers were not present in the region during the period. Heavy amounts of rain were recorded at some stations, while neighboring stations observed little rain. The above features indicate that rainfall was of a convective nature.

The second criterion to examine is the mass curves of rainfall for the storm. Selected mass curves are shown in figure 2.5. These curves are examined in terms of shape and magnitude. The curves exhibit fairly short periods of intense rainfall which are separated by longer periods without rain. The spatial correlation of precipitation with distance diminishes rapidly. The rainfall also was not of a steady nature. Therefore, the criteria for mass curves indicate the storm to be a convective rainfall event.

The isohyetal pattern of the storm also provides clues to the type of rainfall event. Figure 2.5 showed an isohyetal pattern for this storm. The pattern displays a very large area of rainfall with several separate centers. These two criteria eliminate the simple convective event. The ratio of the width of the isohyetal pattern to the length is slightly less than 0.8 based on the 2-in. isohyet. Cyclonic storms tend to have isohyetal patterns which are somewhat elliptical as compared to complex convective storms, whose patterns are characterized by isolated centers, each of which is nearly circular. Rainfall between centers is not uniform and indicates the analysis could have been done in separate parts. Therefore, the isohyetal pattern for this storm is not clearly of any single group. Preponderance of evidence indicates a group within the convective class.

The effective storm duration can be determined from information provided on the pertinent data sheet in "Storm Rainfall." The total storm area, or an area size that includes at least 90 percent of the volume of storm rainfall, is used for this determination. Using the larger area sizes, the effective duration for the Penrose, CO storm is 2.5 days. This is longer than the key duration of one day for a convective storm. This criteria implies cyclonic precipitation.

The total storm area can be determined from the 2 in. isohyet on the isohyetal pattern already presented (fig. 2.5). An alternative source is the storm area information presented on the pertinent data sheet from "Storm Rainfall." For the Penrose, CO storm, the storm area from the pertinent data sheet is 144,000 mi^2. This factor also indicates a cyclonic-type storm.

Three of the five criteria considered have supported the selection of the convective group. However, the criteria should not be weighted equally. In weighting the criteria, the effects of the terrain over the region must be considered. The CD-103 region contains some areas where orography contributes to the volume of precipitation in storms. It is particularly important in considering the mass curves of rainfall and the isohyetal pattern. In the review of the Penrose, CO storm, the first three criteria should be considered more important than the final two criteria. This is considered valid even though this storm occurred over both orographic and nonorographic regions. The latter two criteria were de-emphasized because the limits for convective storms, of one day duration and 10,000-mi^2 area, should be relaxed when a group of related convective events are considered together as one storm. Clearly the mass rainfall curves demonstrate that the Penrose storm fits in this category. Additionally, no cyclonic weather system is present near the area of heavy rainfall at the time. Based on the examination of the five criteria it is concluded that the Penrose storm belongs in the convective group.

2.5.2.2 Simple/Complex. Having placed the storm in the convective group, the final decision is a choice between a complex or simple storm. The effective storm duration and total storm area were much greater than the limiting values of 6 hr and 500 mi^2 for simple convective storms. The total storm area was 144,000 mi^2. Examination of mass curves of rainfall and the isohyetal pattern indicate that the storm could have been analyzed in several sections, though each of these sections would also have exceeded the 6-hr and 500-mi^2 criteria for a simple convective storm. The Penrose storm was given a final classification as a complex convective storm.

2.5.3 Classification of Storms by Type

All important storms (table 2.2) considered in developing PMP estimates for the study region were examined and classified by storm type. Some additional storms from the more comprehensive list of major storms (table 2.1) were also classified by storm type to aid in the initial determination of storm transposition limits. The storms are listed in table 2.3, grouped by appropriate storm type. Within each storm type, the storms where orography played a significant role in the precipitation process are grouped separately from those where orography

Table 2.3.--List of storms of record considered for CD-103 region by storm type

Storm number	Name	Date
	Low Pressure System	(Orographic)
1.	Ward District, CO	May 29-31, 1894
3.	Big Timber, MT	April 22-24, 1900
6.	Boxelder, CO	May 1-3, 1904
7.	Spearfish, SD	June 2-5, 1904
10.	Warrick, MT	June 6-8, 1906
12.	Choteau, MT	June 21-23, 1907
13.	Evans, MT	June 3-6, 1908
14.	Norris, MT	May 22-24, 1909
19.	Ft. Union, NM	June 6-12, 1913
28.	Browning, MT	September 27-28, 1919
30.	Fry's Ranch, CO	April 14-16, 1921
36.	Hays, MT	June 16-21, 1923
45.	Westcliffe, CO	April 19-22, 1933
50.	Circle, MT	June 11-13, 1937
52.	Big Timber, MT	May 17-20, 1938
68.	Dupuyer, MT	June 16-17, 1948
71.	Belt, MT	June 1-4, 1953
75.	Gibson Dam, MT	June 6-8, 1964
79.	Broomfield, CO	May 5-6, 1973
	Low Pressure System	(Least Orographic)
86.	May Valley, CO	October 18-19, 1908
16.	Knobles Ranch, MT	September 3-6, 1911
20.	Clayton, NM	April 29-May 2, 1914
32.	Springbrook, MT	June 17-21, 1921
38.	Savageton, WY	September 27-Oct. 1, 1923
58.	McColleum Ranch, NM	September 20-23, 1941
61.	Dooley, MT	March 13-17, 1943

Table 2.3.--List of storms of record considered for CD-103 region by storm type - (continued)

Storm number	Name	Date
	Cold Front	(Orographic)
8.	Rociada, NM	September 26-30, 1904
23.	Tajique, NM	July 19-28, 1915
33.	Denver, CO	August 17-25, 1921
35.	Virsylvia, NM	August 17, 1922
37.	Sheridan, WY	July 22-26, 1923
57.	Campbell Farm Camp, MT	September 6-8, 1941
59.	Tularosa, NM	September 27-29, 1941
77.	Big Elk Meadow, CO	May 4-8, 1969
	Cold Front	(Least Orographic)
15.	Half Moon Pass, MT	June 7-8, 1910
25.	Lakewood, NM	August 7-8, 1916
44.	Porter, NM	October 9-12, 1930
56.	Prairieview, NM	May 20-25, 1941
62.	Colony, WY	June 2-5, 1944
	Tropical Cyclone	(Orographic)
27.	Meek, NM	September 15-17, 1919
60.	Rancho Grande, NM	Aug. 29-Sept. 1, 1942
	Tropical Cyclone	(Least Orographic)
105.	Broome, TX	September 14-18, 1936
112.	Vic Pierce, TX	June 23-28, 1954
116.	Medina, TX	August 1-4, 1978
117.	Albany, TX	August 1-4, 1978
	Complex Convective	(Orographic)
11.	Ft. Meade, SD	June 12-13, 1907
29.	Vale, SD	May 9-12, 1920
31.	Penrose, CO	June 2-6, 1921
41.	Cheesman, CO	July 19-24, 1929
46.	Kassler, CO	September 9-11, 1933
53.	Loveland, CO	Aug. 30-Sept. 4, 1938
54.	Waterdale, CO	Aug. 31-Sept. 4, 1938
66.	Ft. Collins, CO	May 30, 1948
78.	Rapid City, SD	June 9, 1972
81.	Big Thompson, CO	July 31-Aug. 1, 1976
	Complex Convective	(Least Orographic)
21.	Malta, MT	June 12-14, 1914
40.	Beach, ND	June 6-7, 1929
42.	Valmora, NM	August 6-11, 1929
43.	Gallinas Plant Station, NM	September 20-23, 1929

Table 2.3.--List of storms of record considered for CD-103 region by storm type - (continued)

Storm number	Name	Date
47.	Cherry Creek, CO	May 30-31, 1935
101.	Hale, CO	May 30-31, 1935
49.	Ragland, NM	May 26-30, 1937
108.	Snyder, TX	June 19-20, 1939
111.	Del Rio, TX	June 23-24, 1948
72.	Buffalo Gap, Sask.	May-30, 1961
73.	Lafleche Sask	June 12-13, 1962
74.	Bracken, Sask	July 13-14, 1962
76.	Plum Creek, CO	June 13-20, 1965
114.	Glen Ullin, ND	June 24, 1966
82.	White Sands, NM	August 19, 1978
	Simple Convective	(Orographic)
48.	Las Cruces, NM	August 29-30, 1935
67.	Golden, CO	June 7, 1948
	Simple Convective	(Least Orographic)
55.	Masonville, CO	September 10, 1938

played a minimal role. The simple convective storms listed at the end of the table are among those which are considered appropriate for use in determining local storm criteria. Development of the local storm criteria is discussed more completely in chapter 12. The locations of the important storms (table 2.2) for determining PMP, identified by appropriate storm type, are shown in figure 2.31.

Tracks of tropical storms listed in table 2.4, are shown in figure 2.32. The tracks are composed of two segments. Solid lines are tracks extracted from Neumann et al. (1981), and dashed line segments are extrapolated using either surface weather observations at 0600 or from reported precipitation amounts. The

Table 2.4.--Dates of tropical storms affecting southern portion of CD-103 region

From Neumann et al. (1981)	Plotted in figure 2.32	From Neumann et al. (1981)	Plotted in figure 2.32
7/13-22/09	7/21-26/09	9/10-14/36	9/13-14/36
8/20-28/09	-	9/11-16/41	-
6/22-28/13	6/27-28/13	8/21-31/42	8/29-9/1/42
8/12-19/16	8/18-21/16	8/24-29/45	8/27-31/45
9/12-15/19	9/14-18/19	7/31-8/2/47	-
6/12-16/22	-	6/24-26/54	6/25-28/54
9/6-7/25	-	6/14-16/58	6/15-16/58
6/26-29/29	6/28-7/1/29	7/22-27/59	-
8/11-14/32	-	8/5-8/64	-
7/21-26/34	-	7/30-8/5/70	8/3-5/70

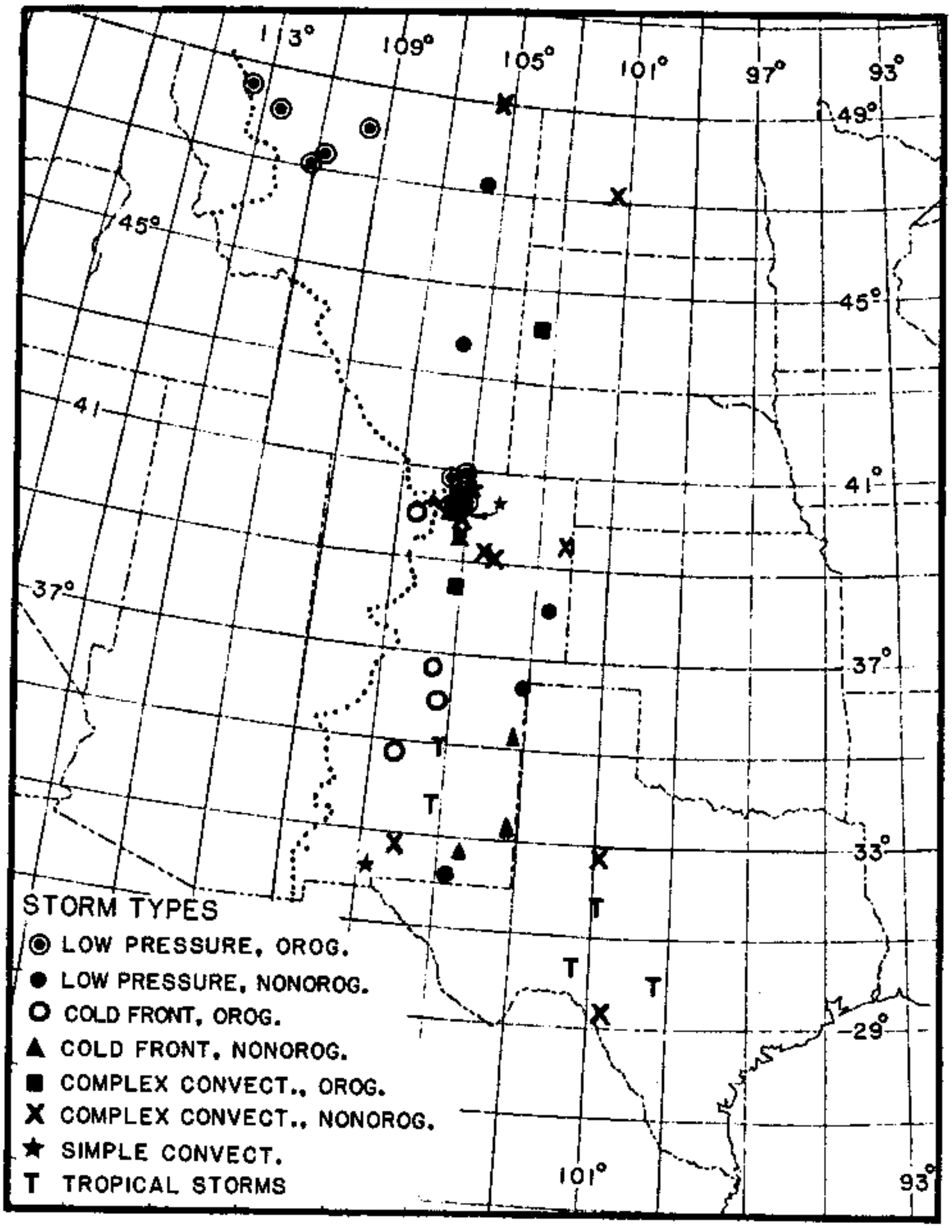


Figure 2.31.--Location of table 2.2 storms by storm type.

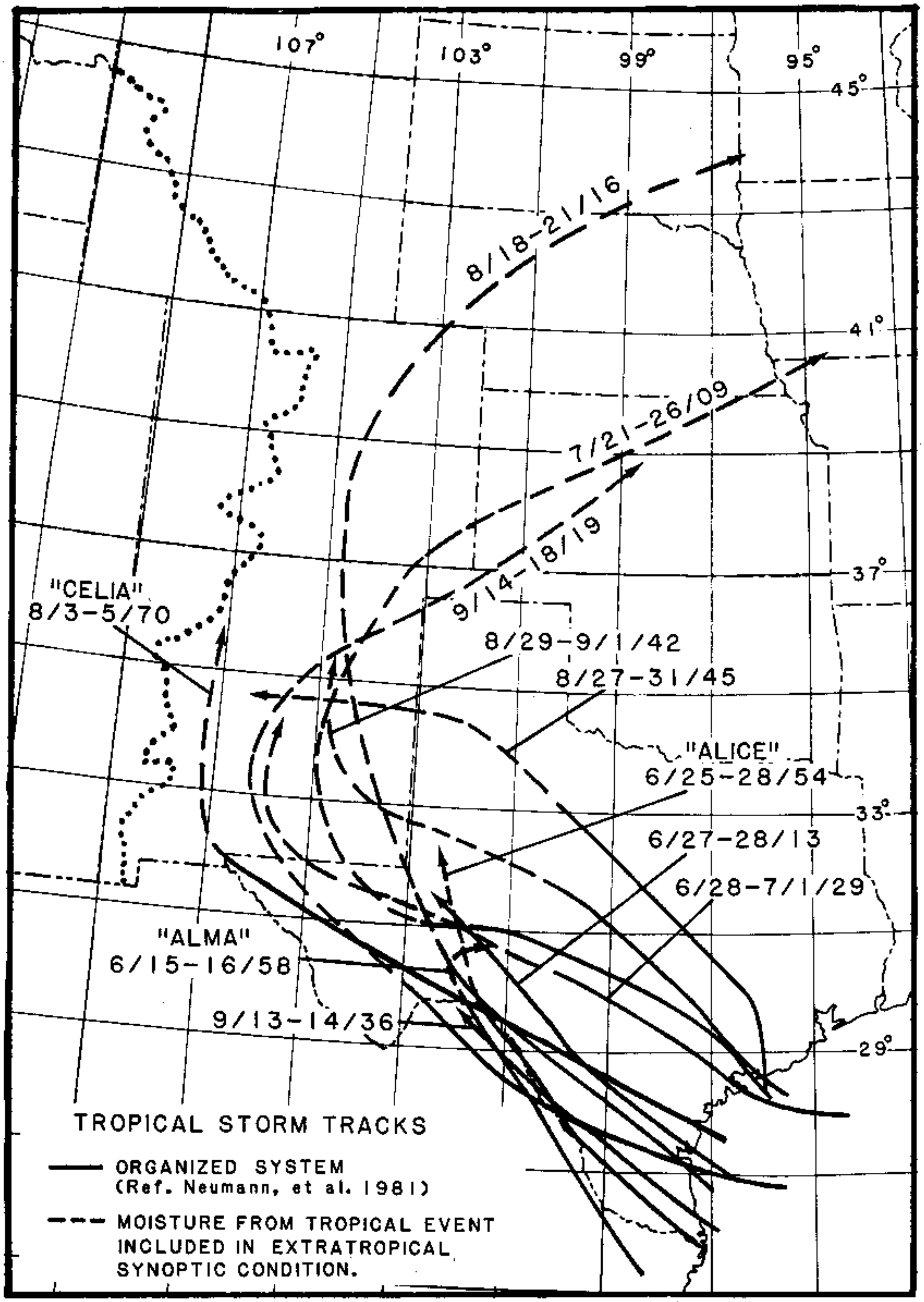


Figure 2.32.--Tracks of tropical storms affecting the southern part of CD-103 region.